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MECHANICAL PROPERTIES OF STANDARD AND COMMONLY FORMULATED NHL MORTARS USED FOR RETROFITTING

Figueiredo, C.¹, Lawrence, M.¹, and Ball, R. J.¹

¹BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, Bath, BA2 7AY, United Kingdom

ABSTRACT: Selecting materials for retrofitting of historic and heritage buildings can be challenging. These materials must be sufficiently compatible and durable without risk of damage to the existing fabric. Therefore, mechanical properties of the retrofitting mortars are of great importance.

Natural Hydraulic Lime (NHL) binders are classified according to their compressive strength at 28 days of aging and lime content using standard EN 459-1. The standard test, however, although important for quality assurance and consistency of binder production, does not reflect the performance of mortars manufactured and used on-site, since these use different aggregates and water/binder ratios.

This study investigates binder classifications, NHL 2, 3.5 and 5, from a single supplier and compares the standard formulation as defined in EN 459-1, with a formulation commonly used as a conservation mortar with 1:2 binder:aggregate ratio.

The 28 day compressive strength of mortars manufactured using a formulation typical for conservation differed in strength from the standardised samples used to classify the binders. At later ages, some mortars were found to have a greater compressive strength than that implied from their classification.

This study concludes that the prediction of aged mortar properties using the standard classification is problematic. The basis for development of a model to predict the performance of aged mortars based on chemical and physical properties of the binders is identified. The model we propose to develop from this work will allow conservators to predict strengths more accurately and reduce the risk of building damage attributed to the use of mortars with inappropriate strength.

Keywords – Mortars for retrofitting; Natural Hydraulic Lime; Mechanical properties

1. INTRODUCTION

Natural Hydraulic Lime (NHL) binders have been used extensively in the mortars and renders of many historic buildings. Currently it is commonly used to repair eroded mortars, replace harmful strong cement and strong hydraulic mortars used inappropriately for repairs and to protect historic fabric by acting sacrificially. Mortars used in retrofitting works are required to be compatible with the existing materials in terms of aesthetics, chemical properties as well as physical and

mechanical characteristics (Henry & Stewart 2011; Feilden 2003; Schueremans et al. 2011).

Compatibility is essential to avoid materials that can cause damage to the existing fabric. The surface characteristics of a mortar, their mechanical properties and porous structure are of great importance along with the chemical compatibility. Compressive strength is an important property when the mortar is supporting a significant load however in many applications the porosity, permeability and flexural strength, which often determine the plasticity or ability of the mortar to accommodate movement, are of greater importance. A low compressive strength, weaker than the historic fabric, with good flexibility, is required for the mortar to act effectively as a sacrificial layer thus protecting the masonry and the historic host fabric. This provides the ability for repair mortars to disintegrate under mechanical stress or chemical attack without subsequent damage to the substrate (Van Balen et al. 2005; Schueremans et al. 2011; Henry & Stewart 2011; Cizer et al. 2010; Forsyth 2008).

Hydraulic lime binders are manufactured by calcining crushed limestone containing clay. The clay minerals present in the limestone are sometimes called impurities. When burned at temperatures between 900°C and 1050°C the carbon dioxide is dissociated. The silica and alumina from the clay then form reactive silicate and aluminate phases (Figure 1).

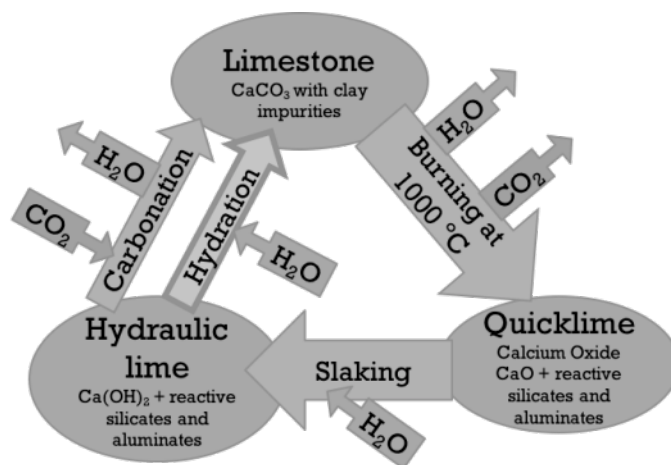


Figure 1: Natural Hydraulic Lime cycle

The initial set of hydraulic lime mortars is much faster than that of air lime, which is attributed to the hydraulic reactions. The calcium silicates and aluminates react with water forming calcium silicate hydrates and calcium aluminate hydrates. Further strength develops from the continued process of hydration and over the longer term carbonation of free lime. CO_2 diffuses through the porous structure reacting with the calcium hydroxide and the hydration products,

resulting in CaCO_3 and amorphous silica and alumina. The process of hydration and carbonation depend on the amount of hydraulic phases existing and on the calcination temperature of the original limestone. (Holmes & Wingate 2002; Forsyth 2008; Henry & Stewart 2011; Allen et al. 2003; Lanas et al. 2004; El-Turki et al. 2010; Livesey 2002).

Before the modern classification of the EN 459-1, NHLs were classified according to the Cementation Index (CI) firstly proposed by Vicat (1837 (Facsmile1997)) as a method to predict the performance of hydraulic limes based on the likely hydraulicity of the raw materials of the binder. This Index balances the weight contribution of the different components that can be detected from chemical analysis of the limestone. The most common expression found in the literature for the CI is represented by Eq.1.

$$CI = \frac{2.8SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3}{CaO + 1.4MgO} \quad (\text{Eq. 1})$$

$$HI = \frac{SiO_2 + Al_2O_3}{CaO} \quad (\text{Eq. 2})$$

The Hydraulicity Index (HI) (Eq. 2) is also described in the literature as a method for hydraulic lime classification, balancing the most active oxides (Holmes & Wingate 2002; Elsen et al. 2012).

The common classification of limes reported by Holmes & Wingate (2002) is described in Table 1.

Table 1: Cementation Index for the various types of building lime

Lime description	Cementation index (CI)	Active clay in the limestone
Fat limes	Close to zero	Very little clay
Slightly hydraulic limes	0.3 to 0.5	Around 8%
Moderately hydraulic limes	0.5 to 0.7	Around 15%
Eminently hydraulic limes	0.7 to 1.1	Around 25%
Natural cement	1.7	Up to 45%

These earlier classifications have now been superseded by the European standard EN 459-1:2010 which classifies the NHL according to the minimum quantity of available lime, as Ca(OH)_2 , and the compressive strength at 28 days as shown in Table 2.

Table 2: NHL classification and tolerances according to EN 459-1:2010

Lime type	Available lime as Ca(OH)_2	Minimum compressive strength at 28 days - tolerance values in brackets (MPa)
NHL2	≥ 35	2 (2-7)
NHL3.5	≥ 25	3.5 (3.5-10)
NHL5	≥ 15	5 (5-15)

There is wide overlap among the three classifications allowing a high variability of limes to be classified as the same type. The test at 28 days can also be misleading when characterising and classifying less hydraulic limes where the majority of strength is gained through carbonation over the longer term. (Henry & Stewart 2011; Elsen et al. 2012).

NHL2 binders are often preferred for conservation applications where low strength is required however the EN 459-1 classification is insufficient to guarantee that undesirable higher strengths will not be achieved. There is currently a need for a classification which takes into account the lime setting processes and more reliably predicts the strength of mortars manufactured from limes at ages of a year or more.

2. MATERIALS AND METHODS

Standard mortar prisms (160 x 40 x 40 [mm]) were prepared using 2 distinct formulations, a standard formulation used for lime classification (BS EN 459) and a volumetric formulation commonly used in conservation works. For each formulation type, 3 different classification binders were selected. This allowed the differences between the mortar mix designs used on site to be compared with the mechanical performance predicted from the binders' classification. Based on the binder's chemical and physical characterisation, the foundation of a model to predict mortar performance is described.

2.1 Binders

Bulk density was determined using the process described in BS EN 459-2:2010 and the surface area was determined by BET nitrogen adsorption analysis using a Micromeritics 3Flex (Table 3). Particle size distribution was obtained testing the dry powder in a Malvern Mastersizer 2000 and obtaining the frequency of the particle size related to the volume (Figure 2. Particle size distribution).

Table 3. Physical properties of the binders: bulk density and surface area

Binder	bulk density (g/cm ³)	surface area (m ² /g)
NHL2	0.64	5.4579
NHL3.5	0.58	5.9218
NHL5	0.59	6.7700

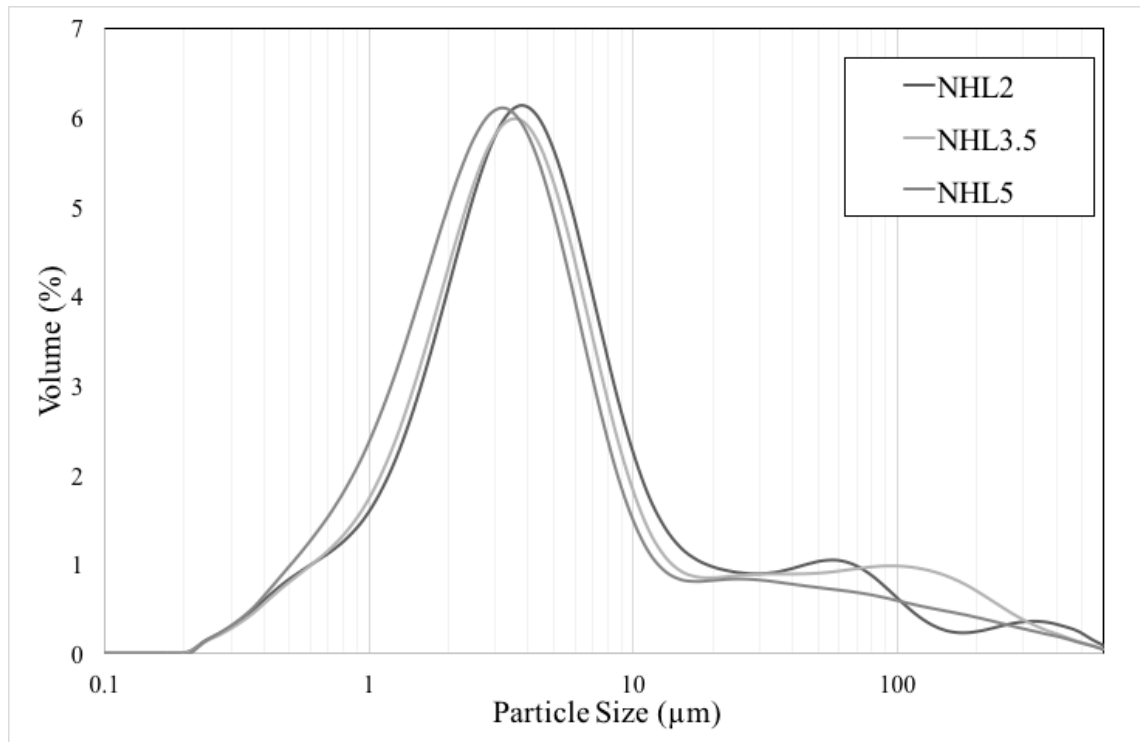


Figure 2. Particle size distribution

XRD analysis (Table 4) was performed at ambient temperature using a Bruker-AXS D8 powder X-ray diffractometer. The equipment was operated at 40kV, 40mA and the source of radiation was Cu-K α X-ray of wavelength $\lambda = 1.5405 \text{ \AA}$. The step was 0.02° , from 4 to 75° (2θ).

Table 4. XRD qualitative mineral composition. ++ Strong signal, identified by 3 or more major peaks; + Moderate signal, identified by 3 peaks of intensity <20% of maximum; R Residual concentration.

Binder	Ca(OH) ₂ Portlandite	CaCO ₃ Calcite	Ca ₂ SiO ₄ Belite	Ca ₃ SiO ₅ Alite
NHL2	++	+	+	+
NHL3.5	++	+	+	+
NHL5	++	+	+	+

XRF analysis (Table 5) was performed on pellets of diameter 40mm and

thickness 2mm pressed from the binders and analysed using an EDAX Eagle II Energy Dispersive XRF spectrometer with Rhodiun X-ray, operated at 25kV and 1mA for 100 seconds in multiple spots per sample for the spectrum acquisition. The Loss on Ignition (LOI) was determined by burning 1g of material [± 0.001] at 950°C until sample mass stabilization.

Table 5. Oxide composition. Cementation and hydraulicity index according to (1) and (2)

Oxide	NHL2	NHL3.5	NHL5
CaO	66.38	65.82	64.23
SiO ₂	7.8	8.40	7.80
Al ₂ O ₃	1.63	2.51	2.35
MgO	2.37	1.93	2.16
Fe ₂ O ₃	2.1	1.63	1.93
SO ₃	0.37	0.50	0.42
K ₂ O	0.89	1.10	1.09
Na ₂ O	0.31	0.64	0.58
TiO ₂	0.16	0.20	0.16
MnO	0.05	0.05	0.07
LOI	17.95	17.23	19.22
CI	0.36	0.40	0.38
HI	0.14	0.17	0.16

2.2 Manufacture and curing of the mortar specimens

To establish the volumetric formulations, bulk density of the aggregate (1.41 g/cm³) was determined using BS EN 1097-3:1998. The quarzitic nature was assessed from XRF and XRD characterisation where the major oxide detected was SiO₂ corresponding to the mineral quartz. Mortar prisms with dimensions 160×40×40 [mm] were prepared using NHL 2, 3.5 and 5 binders sourced from the same manufacturer with a binder:aggregate (b/a) volumetric ratio of 1:2 and a spread, measured by flow table (BS EN 1015-3:1999) of 165±10 [mm]. Specimens were prepared and cured according to the BS EN 1015-11:1999. Compressive and flexural strength was then measured at 7, 14, 28, 91 and 180 days, following the method described in BS EN 1015-11:1999. Table 6 shows the characteristics of the formulations manufactured by volume, the spread and the water/binder (w/b) ratio in mass.

Table 6. Common formulations characteristics (1:2 b/a volumetric formulation)

Binder	Binder (g)	Sand (g)	Water (g)	b/a (w/w)	Spread (mm)	w/b
NHL2	2640	11676	2508	1:4.42	160	0.95
NHL3.5	2420	11852	3178	1:4.90	161	1.31
NHL5	2475	11923	2930	1:4.82	156	1.18

Using the protocol present in the BS EN 459 for binder classification, 3 sets of prisms (NHL2_S, NHL3.5_S, and NHL5_S) for testing at 28 days were prepared with the specifications present in Table 7.

Table 7. Standard formulations components

Binder	Binder (g)	Sand (g)	Water (g)	w/b
NHL2_S	450	1350	248	0.55
NHL3.5_S	450	1350	270	0.60
NHL5_S	450	1350	270	0.60

This standard formulation is based in a 1:3 (w/w) binder:aggregate ratio and the quantity of water is dependent on the bulk density of the binder and the desired classification (Table 8). The aggregate used is standardized quartz based sand.

Table 8: BS EN 459 standard formulations prescription

Type	Bulk density (kg/dm ³)	Water (g) ± 2	w/b
NHL5	>0.6	225	0.5
NHL2; NHL 3.5	>0.6	248	0.55
NHL 2; NHL 3.5; NHL5	≤0.6	270	0.6

3. RESULTS

Two sets of results are presented in this study: the 28 days strength from the commonly formulated mortars for conservation and retrofit are compared to the standard formulated mortars used to classify the binders. The evolution of compressive strength of the three different classified binders from the same manufacturer are also compared.

3.1 Compressive strength at 28 days from the 2 formulation types

Figure 3 shows the differences observed when comparing the compressive strength at 28 days for the commonly formulated mortars and the mortars produced using the standard process with the standard sand.

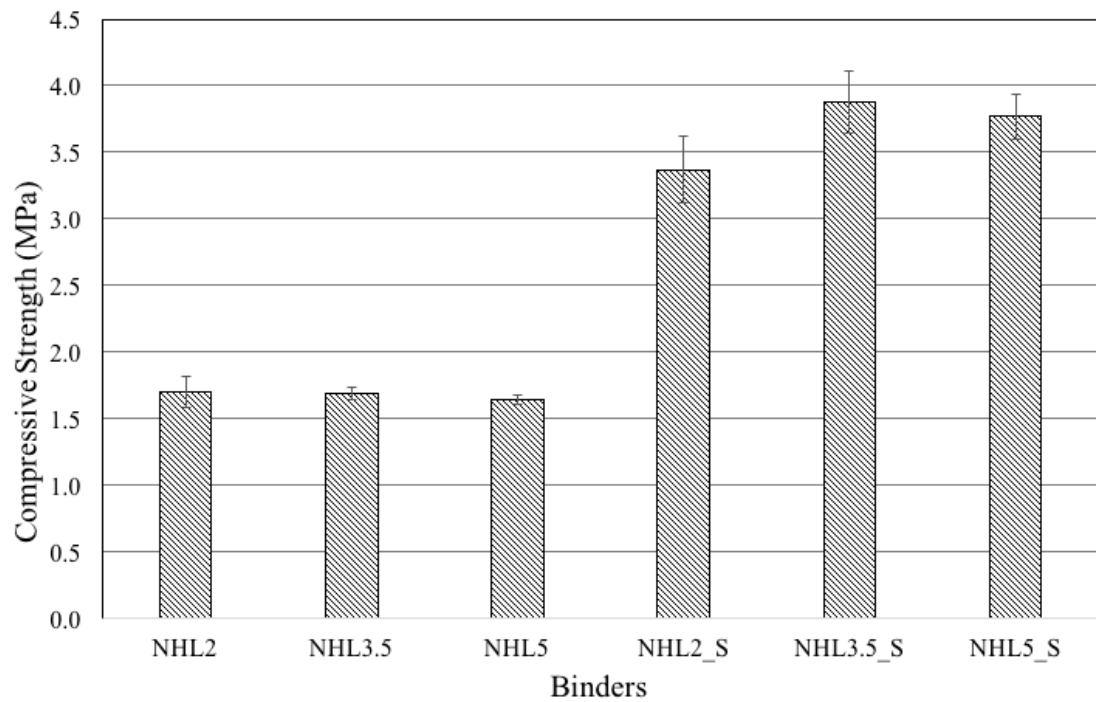


Figure 3. 28 day compressive strength for common and standard formulated mortars

At 28 days the commonly formulated mortars exhibit a lower strength than the standard mortars and a lower strength than predicted by their classification. Both formulations led to similar values for the different classifications and in case of NHL5_S lower values than that expected from the classification of that binder.

3.2 Evolution of the compressive strength of the binders

Compressive strength of the non-standard formulation is shown in Figure 4. As expected the 3 binders gain strength until 360 days.

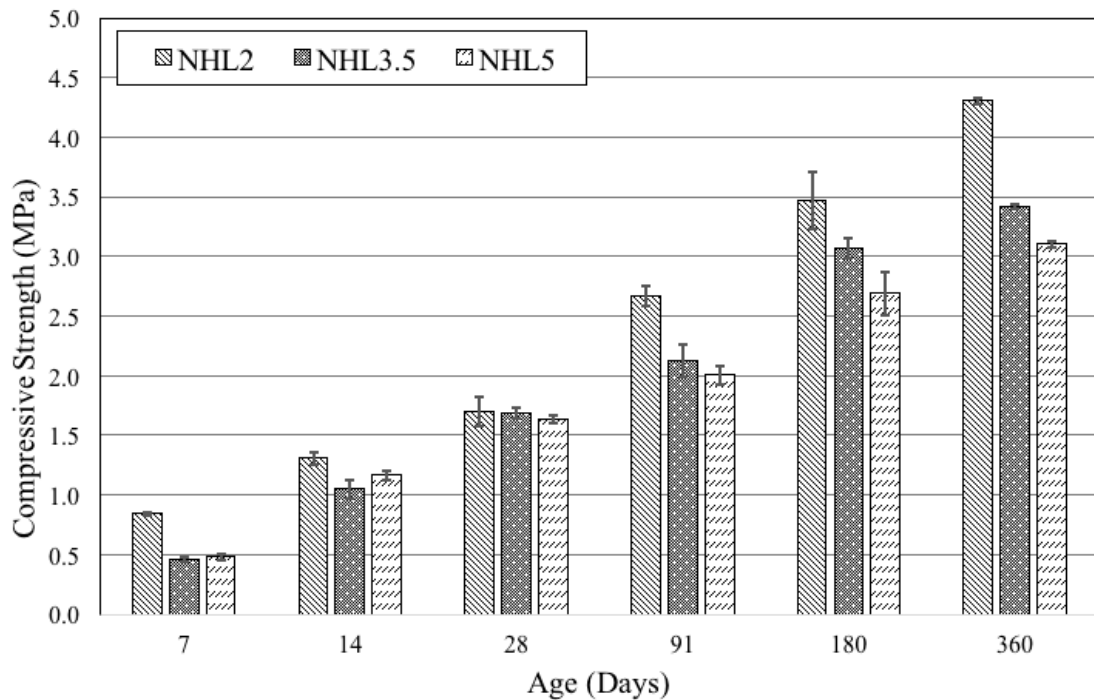


Figure 4. Evolution of the compressive strength of the common formulated mortars

The mortar manufactured using the NHL2 binder gains strength at a higher rate when compared to the mortars from the NHL3.5 and 5 binders. For ages of 91 days and greater the NHL2 mortar is considerably stronger than the others. This is an unexpected result when the mortar classification is considered.

4. DISCUSSION

Comparison of the two formulation types indicates that the classification given by the BS EN 459-1 does not reflect the actual performance of the mortars manufactured with a common binder/aggregate ratio and sand. This is due to the standard requiring a standard sand, which would not be used realistically on a construction site and unrealistic w/b ratio.

The 3 different binders had similar chemical composition, the evolution of the strength gain reflects the w/b ratio where the lower ratio from the NHL2 resulted in a stronger mortar at 360 days. The lower w/b ratio for the same workability, measured by spread in the flow table, reflects the lower surface area of the NHL2. NHL5 with a higher surface area and a lower w/b ratio showed less spread in the flow table.

The three hydraulic lime mortars commonly formulated had compressive strengths below their classification at 28 days. At 91 days, NHL2 had achieved

the 2 MPa threshold whereas the NHL3.5 and 5 mortars did not achieve strengths required by their classification at the 360 day period. At 180 days the NHL2 mortar reached the lower limit of the compressive strength for the next strongest classification group (NHL3.5).

When designing a mortar to achieve a maximum compressive strength according to the standard classification the fact that the compressive strength achieved at 28 days can be as much as 50% less than the long term compressive strength should be considered. The classification allows for a high range of variation in compressive strength due to the tolerance of their classification.

The standard classification can lead to an underestimation of eventual strength for later ages, as demonstrated by the 360 days compressive strength of the NHL2 binder measured as 4.3 MPa. In addition, for the other binders it has been demonstrated that it is possible to overestimate the compressive strength of NHL3.5 and NHL5 mortars, as they did not meet the strength predicted by their classification.

When the binders present similar chemical characteristics, the variability of the final properties is determined by their physical properties. Therefore, a model to predict mortar properties over long term aging should take both chemical and physical parameters into consideration. A model reflecting these factors is expected to be achieved and aid professionals to make an appropriate selection of the materials.

CONCLUSION

The standard classification does not reflect the actual performance of the NHL mortars manufactured with common sand and formulated by a usual volumetric binder aggregate ratio for the workability commonly desired by practitioners. The actual performance and properties of the mortar is determined by the chemical and physical properties of the binders and the mixing parameters (proportion between binder, water and aggregate and the needed workability).

Those specifying mortar formulations should exercise caution when using EN 459-1 to predict mortar properties. Mortars expected to have low compressive strengths can achieve much higher strengths than those implied by the binder classification. In contrast, mortars expected to achieve higher strengths can present lower compressive strength not reaching the minimum for their

classification.

A model relating the chemical composition and physical characteristics of the binders will aid the appropriate selection of the materials to use when retrofitting historic and heritage buildings.

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